

FREEZING IN A REFRIGERATOR OF ENGINEERING PRODUCTS FROM SAND-WATER MIXTURES

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DOI: 10.17973/MMSJ.2026_06_2026114

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The work establishes a number of features regarding the mechanics of freezing wet quartz sands when manufacturing products of limited sizes from them. Products of limited sizes from frozen sand in foundry production are casting models used for manufacturing volumetrically closed and detachable casting molds using the SMS-process method, frozen casting molds and rods, etc. The work used quarry quartz sand of the 1K₂O₂O₂ brand and tap water. The mass was measured on a VTA-60/6-73-AL-2 scale with an accuracy of ±1 g. The temperature was measured with an alcohol thermometer of the TTZ type and a chromel-copel thermocouple complete with an electronic device of the STC-1000 brand with an accuracy of ±1 °C with video recording of temperature changes over time with an interval of 1 s. Drying of sand was carried out in a microwave oven with a magnetron power of 900 W and a microwave radiation frequency of 2.45 MHz. Freezing of wet sand was carried out in a refrigeration chamber with a capacity of 17 kg/day at a temperature of -20 °C. According to the results of the research, it was found that flat products with a thickness of 10 mm, regardless of the water content (up to 12.5% above), under conditions of unidirectional heat removal, cool to 0 °C faster than dry quartz sand. Freezing of wet sand under conditions of multidirectional heat removal from it leads to a significant migration of water in the sand in the direction of gravity, i.e. from the solidification front of wet sand to a surface with a higher temperature, which is in the direction of movement of unfrozen water. Increasing the initial temperature of wet sand contributes to an increase in the rate of its cooling to 0 °C and the time of solidification of water, but increases the total time of solidification of wet sand.

KEYWORDS

Sand, water, sand-water mixture, freezing, cold storage, foundry production

1 INTRODUCTION

Freezing mechanics is a branch of solid mechanics that studies the processes and effects caused by the phase transition (from liquid to solid) of substances at low temperatures. Within the framework of freezing mechanics, problems that arise during phase transitions in materials at low temperatures (deformations, stresses, fractures, properties of frozen materials, etc.) are considered [Li 2022]. An applied component of freezing mechanics is cryotechnology in geotechnics [An 2021], construction [Xi 2024], climatology [Chen 2022], medicine [Li 2024], food [Jha 2024], chemical [Freiburghaus 2020], metallurgical [Fang 2025] and other industries.

In foundry production, a method for manufacturing frozen casting molds from wet sand-clay molding mixtures was proposed by A. Lunyov (1934), according to which sand-clay casting molds were cooled to a temperature of -24...-25 °C before pouring with melt. The manufacture of frozen casting molds from pure quartz sand was proposed by B. Bondarevsky (1941). The use of casting molds from frozen wet sand or sand-clay mixtures made it possible to significantly improve the quality of small and medium-sized castings from steel, cast iron, bronze, brass, and aluminum alloys, but the lack of the necessary productive refrigeration equipment at that time did not allow this method to be scaled up in foundries. Therefore, since the invention of the production of frozen casting molds, their freezing was for a long time carried out only using seasonal natural cold, that is, in separate foundries that were located in areas with cold climatic conditions [Shinsky 2017a].

With the advent of high-performance refrigeration technology [Shinsky 2016a,b], scientists and researchers (O. Shinsky, V. Droshenko (2009) and others) began to study the mechanics of freezing wet sands as objects of finite dimensions (foundry molds and cores). As a result, during the existence of foundry cryotechnology, the thermophysical and technological indicators of frozen sand-water mixtures in the composition of foundry molds and cores were studied and determined. In particular, V.M. Gruzman (1975...1982) determined the mechanical, thermophysical and technological properties of foundry molds from frozen sand-water mixtures, substantiated the impossibility of increasing the solidification rate of castings in such molds, etc. Investigating the heat transfer process in frozen sand foundry molds, M.I. Zamyatin developed compositions of non-stick coatings (paints) for molds and rods, investigated the regularities of heat transfer in the system "liquid metal – coating – frozen mold (rod)" [Lysenko 2014], etc. One of the significant disadvantages of the technology for manufacturing frozen casting molds in cold storage is the relatively long time of freezing. Today, pre-cooled model equipment, wet sand, high-performance cold storage chambers, etc., are used to reduce the freezing time of casting moulds. In some foundries in England, Japan, Germany, etc., liquefied nitrogen, carbon dioxide or propane are used for artificial freezing of casting molds, which allows for reducing their manufacturing time by several orders of magnitude (up to several minutes) [Shinsky 2017b, Saga 2011]. Currently, any technology for manufacturing casting molds and cores in foundries is considered from the point of view of its economy, efficiency and environmental friendliness [Gaspar 2018]. In particular, among the known methods for manufacturing castings in volumetrically closed casting molds in terms of casting quality, there is casting from melted models. However, such casting is very expensive in terms of cost and requires both increased time and material costs and the performance of a significant number of technological operations in the manufacture of casting molds. Casting by gasified models is relatively inexpensive and does not require much time and

materials for the manufacture of casting molds. Still, in view of the sanitary and hygienic conditions of production and environmental safety, it cannot be classified as a safe method. In addition, the features of the casting method by gasified models make it impossible to use it for the manufacture of castings from steel and other alloys, except for cast iron, in which carbon dissolves in the liquid state. Today, the environmental component of any material, the process of its use and disposal, has become an obligatory part of the characteristics of any production. From this point of view, the use of frozen casting molds and rods, where the binder is water, is an indisputable and significant positive component in comparison with molding and rod mixtures, in which synthetic resins, salts with acidic properties, orthophosphoric acid, lignosulfonate, dextrin, molasses, mineral, polystyrene, natural oils, etc. are used as a binder. Artificial freezing of casting molds and rods from sand-water mixtures in refrigeration chambers is a long, relatively expensive process, and the use of liquefied gases (30 kg or 37 liters of liquefied nitrogen to freeze 100 kg of moulding mixture) is not only expensive, but also an increased danger due to the possibility of frostbite of workers. Nevertheless, a certain reduction in the cost of production of castings in frozen molds from wet quartz sand is achieved due to the absence in this process of several technological operations inherent, for example, in the technology of manufacturing molds from sand-clay mixtures [Shinsky 2017b, Lee 2024]. Currently, frozen casting molds are oriented for the production of castings for general engineering purposes with a mass of up to 0.5 to 200 kg. Nevertheless, despite the advantages of using water as a binder material for casting molds and cores, the industrial nature of the production of liquefied nitrogen and the possibility of purchasing appropriate refrigeration equipment, today in Ukraine these methods have not yet found their industrial implementation in the production of castings. The main reasons for this state of affairs are the duration of the freezing time of wet sand in refrigeration chambers and the danger of frostbite of workers when using liquefied gases.

Based on this, and also taking into account the fact that the mass of the casting model from frozen wet sand is 15...20 times less than the mass of its casting mold, the authors of the work [Patent 125146] a method (SMS-process) for manufacturing casting molds based on disposable casting models from frozen sand-water mixtures has been proposed. The use of such casting models allows the manufacture of both volume-closed and detachable casting molds from environmentally safe sand-liquid glass mixtures, improves the quality of castings, expands the technological capabilities of casting manufacturing, significantly reduces the time for manufacturing casting molds and cores, etc., and solves the problems of recycling spent mixtures.

The purpose of this work is to establish the features of freezing sand-water mixtures in products of final sizes in a refrigeration chamber.

2 STATUS OF THE ISSUE

In the method of manufacturing sand-liquid glass casting molds, the most time-consuming process is the freezing of wet sand (water content in sand 5...10% over 100% quartz sand, by mass) in the equipment. At the same time, the processes that occur during freezing in wet sand within the working space of the equipment are somewhat similar to the processes that occur during freezing in wet soil. This is because frozen wet sand, like other frozen soils, is a multicomponent system that includes solid (including ice), liquid and gaseous phases. As a rule, from the point of view of heat and mass transfer, scientists and researchers consider freezing and frozen soils as a flat semi-infinite body. At the same time, in their studies, Z. Wen (2010),

H. Li (2018), M. Zhelnin (2019), and co-authors note that the process of soil freezing is accompanied by its swelling and the emergence of significant stress in it. The cause of frost swelling is an increase in the volume of soil in the process of converting water into ice. As a result of swelling, under certain conditions, a layer of frozen soil is separated from its unfrozen part. Given the freezing of wet sand in the foundry equipment, this phenomenon can lead to the destruction or gouging of the product (casting mold, rods, casting models and their sprue system) or the destruction of the foundry equipment. According to the data of the work [Solonenko 2024a], the shedding and gouging of products of a frozen sand-water mixture largely depends not only on the amount of water, the initial temperature of the product, but also on the saturation of water with gases. At the same time, the type of water used in the sand-water mixture will probably also affect the strength of the sand-liquid glass mold, which is structured by water vapor from quartz sand previously coated with sodium liquid glass.

In the humidity range up to $\sim 0.25\%$ (more than 100% of the mass of quartz sand), water on the surface of the grains of sand is in a layer several microns thick, which is firmly connected to the surface of the grains of sand and cannot form contact cuffs of moisture at the points of contact of the grains of sand. In this regard, heat exchange between grains of sand in such sand-water mixtures occurs both by the conductive mechanism (thermal conductivity) through the points of contact between the grains of sand, and by the weakly expressed convection mechanism of air in the capillary channels of the sand. With an increase in the humidity of the sand (more than 0.25%), the thickness of the water layer on the surface of its grains of sand acquires a value at which contact water cuffs and, accordingly, surface tension forces arise between the grains of sand. Sand with such a quantity of water loses its inherent natural flowability under the influence of its mass, and therefore is classified as wet on this basis [Repiakh 2019]. The appearance of water cuffs leads not only to the loss of flowability by quartz sand, but also to an increase in the value of the conductive component in heat transfer and a decrease in the share of the convective component. At the same time, with an increase in the share of water in the sand, the density and specific heat capacity of the sand-water mixture increase, which, in particular, linearly depend on the humidity of the sand, the mass fraction of water in the sand. An increase in the share of the conductive component with its constant absolute value of thermal conductivity contributes to an increase in the cross-sectional area of the cuffs, due to an increase in the share of water in the sand. Considering frozen wet soils from the point of view of temperature changes, the authors [Khaksar 2025, Ngo 2022, Chernobrovchenko 2022] among other things, estimate the rate of their heating or cooling and freezing, paying special attention to the theoretical and experimental determination of the coefficients of thermal conductivity and thermal diffusivity. At the same time, concerning sand-water mixtures (wet sand), as a structural model of these mixtures, a simplified scheme of the interaction of two particles in wet sand of the same size and shape is used as a structural model of the processes, which is schematically presented in Fig. 1,a, assuming that each particle has several cuffs (see Fig. 1,b) - water "bridges" connecting it with its neighboring particles.

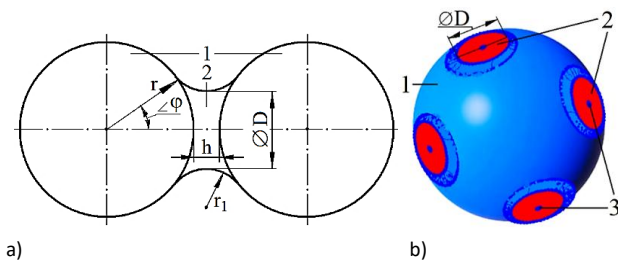


Figure 1. Scheme of water distribution in the area of neighboring grains of sand (a) and the type of cross-sections of cuffs on a grain of sand at $h=0$ (b), which are adopted for calculations: 1 – grain of quartz sand; 2 – water cuff; 3 – point of contact between grains of sand

According to [Valicek 2016, Jurko 2011], for a water cuff located between two spherical grains of sand of the same radius (r) according to the scheme in Fig. 1,a, its geometric parameters can be calculated by the formulas (1), (2).

$$D = 2 \cdot [r \cdot (1 - \cos\varphi) + h/2] / \cos(\varphi + Q), \quad (1)$$

$$r_1 = r \cdot \sin\varphi - [r \cdot (1 - \cos\varphi) + h/2] \cdot [1 - \sin(\varphi + Q) / \cos(\varphi + Q)], \quad (2)$$

where φ is the angle between two rays emanating from the center of a spherical grain of sand, one of which is directed to the center of the cuff, the other to the edge of its meniscus on the grain of sand; h is the distance between neighboring grains of sand connected by the cuff; Q is the contact angle of water wetting of sand particles (for quartz sand $Q = 0$).

According to the experimental data of [Panda 2013a] for a sand-water mixture with porosity from 42 to 54% and a specific surface area of quartz sand from 103 to 384 m^2/kg , its tensile strength increases with decreasing porosity and increasing specific surface area of the quartz sand used, reaching a maximum value of 4.9 kPa at a water content in the mixture of 8% (by mass) with a specific surface area of quartz sand of 384 m^2/kg and porosity of 50%. An increase in the water content in the sand above 8% leads to a decrease in strength regardless of the specific surface area and porosity of the sand. The presence of an extremum at a water content above 8% is apparently associated with a change in shape (initially) and the disappearance of cuffs as such (later) between the grains of sand as their capillary space is filled with water. The size of the cuffs and their number on a grain of sand (sand moisture content) should determine both the level of thermophysical properties of both wet and frozen sand, and, accordingly, the speed and time of its freezing.

Studying soils with different particle sizes and moisture content, the authors of [Zhou 2015] found that the size of soil particles has little effect on thermal conductivity, which mainly depends on the water content in the soil and increases with increasing water content. At the same time, according to [Jurko 2012], freezing of wet sand under conditions of unidirectional heat removal contributes not only to the advancement of the freezing front of the mixture in the same direction, but also to its migration of water in the sand in the opposite direction, that is, from deep layers where the water has not yet frozen. This implies that when freezing wet quartz sand, for example, in a cylindrical container, the largest amount of water will be on the surface of the sand, through which heat is removed from it.

The authors of [Zhen 2018] found that the thermal conductivity of sandy soil depends little on its density and mainly on its moisture content, reaching its maximum value at a water content of 15% in the soil. With a further increase in the water content in the soil, its thermal conductivity stabilizes or decreases slightly. According to [Jurko 2012], soil moisture is one of the main parameters that determine the value of its thermal conductivity and thermal

conductivity and, accordingly, the freezing rate. At the same time, [Panda 2013b] calculates the value of the thermal conductivity coefficient of the soil using the empirical formula (3).

$$a = a_0 + A \cdot \exp \left[-0,5 \cdot \left(\frac{\ln \frac{B_i}{B_{i0}}}{B} \right)^2 \right], \quad (3)$$

where a_0 is the thermal conductivity of dry soil, m^2/s ; A is the difference between the maximum and minimum thermal conductivity of the soil; B is the curve shape parameter (characterizes the peak width); B_i is the volumetric soil moisture, m^3/m^3 ; B_{i0} is the humidity at which the maximum thermal conductivity is achieved.

According to [Panda 2011, Dyadyura 2017], the variables in equation (3) for sandy soil have the following values: $a_0 = (2.03 \dots 4.56) \cdot 10^{-7} m^2/s$, $A = (2.25 \dots 8.04) \cdot 10^{-7} m^2/s$, $B_{i0} = 0.11 \dots 0.35 m^3/m^3$, $B = 0.11 \dots 1.58$. If for pure sand we take $a_0 = 2.03 \cdot 10^{-7} m^2/s$, $A = 2.25 \cdot 10^{-7} m^2/s$, $B_{i0} = 0.25, m^3/m^3$ $B = 0.11$, then the dependence of the thermal conductivity coefficient of quartz sand on its humidity will have the form presented in Fig. 2.

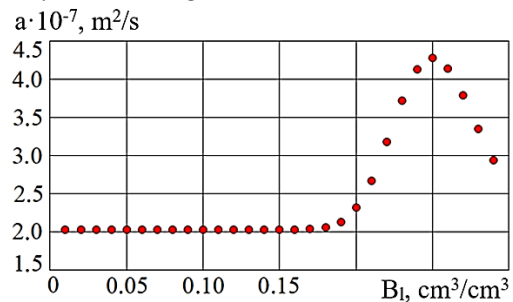


Figure 2. Dependence of thermal conductivity of quartz sand on its water content

From the analysis of the dependence in Fig. 2 it follows that water increases the value of the thermal diffusivity coefficient of wet sand at a content of $\sim 0.18 cm^3/cm^3$ to $0.25 cm^3/cm^3$, which corresponds to a mass of $B_i \approx 10 \dots 13.5\%$. It follows that when the humidity of the sand is less than 10%, the water content in the sand practically does not affect its freezing rate.

During the rise of frozen liqueur forms, the most important indicators of technology are their primary value and vitality. According to data [Pandova 2018, Sukhodub 2018, Shinskiy 2017], quartz sands with 5% water instead are characterised by virtually flattenedness, which is important from the point of view of completeness and completeness of the model equipment in which volcanic sand is frozen. Therefore, in the opinion of the authors, to obtain a sufficient level of value, gas permeability and fluidity of the frozen product, instead of water in the quartz sand, it is necessary to add 5% or 5.3% on top of 100% quartz sand. In [Shinskiy 2016], the authors indicate that the main factors that determine the value of frozen wet sand are its moisture content and temperature, while the inclusion of clay in the sand and the dispersion of its particles are not practical pour into the world.

The greatest value is found in frozen mixtures, which are mixed with 3...5% clay at a temperature of $-20 \dots -25 \text{ }^\circ C$. At the same time, the cost of freezing such sums in relation to the temperature of defrosting (up to an increase in temperature to $-5 \text{ }^\circ C$) is 1:4, so it becomes 30 to 90 degrees [Shinsky 2017a]. To increase the value and reduce the abrasion of frozen liqueur forms, vikorize quartz sand of grade $1K_3O_3O16$ with 5% tap water and 5% bentonite clay at an initial temperature of no more than $-19 \dots -20 \text{ }^\circ C$. The nature of the clay used in the moulding mixture, as well as the method of preparing water and clay before

moulding, also affects the softness and friability of frozen liqueur forms. The greatest value and least soreness is achieved by mixing sand with 5% boiled water and 5% soft bentonite clay. The results are slightly lower in sums with soft clays and carbonated CO₂ water. The average value and one of the lowest susceptibility is the sum of sand with 5% tap water and 5% soft bentonite clay [Solonenko 2018].

Since water and ice in the cuffs have a much higher thermal conductivity than quartz, likely, the freezing time and strength of frozen wet sand are also affected by the quality (structure) of the ice in the cuffs, which, in turn, depends on the gas saturation of the water. In particular, the lower the gas saturation of the water, the denser the ice, the higher the stability of the frozen sand over time. The presence and amount of water-soluble impurities in the source water significantly affect both the nature, size and distribution of gas bubbles in the ice and the viability of frozen sand-water mixtures. The viability of frozen mixtures increases with an increase in the amount of water in them, the density of the ice and the mixture and its homogeneity. For mixtures with clays, the mixture with unswollen kaolin clay has the greatest viability. From the point of view of viability, recommendations have been developed for the manufacture of products from frozen foundry mixtures [Solonenko 2024b].

Despite the significant amount of research conducted to date, several features regarding the mechanics of freezing wet quartz sands in the manufacture of products of limited sizes from them have not been established, which, in particular, are casting models used for the manufacture of volumetrically closed and detachable casting molds using the SMS-process method, casting molds and rods manufactured by freezing sand or sand-clay mixtures.

3 MATERIALS AND METHODS

The work used quarry quartz sand of the 1K₂O₂02 brand and tap water. The studies used quartz sand with a water content of 0 to 12.5% by weight over 100% quartz sand. The mass was measured on a VTA-60/6-73-AL-2 scale with an accuracy of ±1 g. The temperature was measured with an alcohol thermometer of the TTZ type and a chromel-copel thermocouple, complete with an electronic device of the STC-1000 brand with an accuracy of ±1 °C, with video recording of temperature changes over time with an interval of 1 s. As an indicator of the humidity of wet sand, the ratio of the mass of water removed from the sand dried to a constant mass was taken, according to the results of five consecutive tests. Drying of the sand was carried out in a microwave oven with a magnetron power of 900 W and a microwave radiation frequency of 2.45 MHz. Freezing of wet sand was carried out in a refrigeration chamber with a capacity of 17 kg/day at a temperature of -20 °C. Before freezing in the equipment, the wet sand was compacted manually. The dependence of the temperature change of a flat layer of wet sand on time during its freezing with one-sided heat removal was carried out in a device, the scheme of which is given in Fig. 3,a.

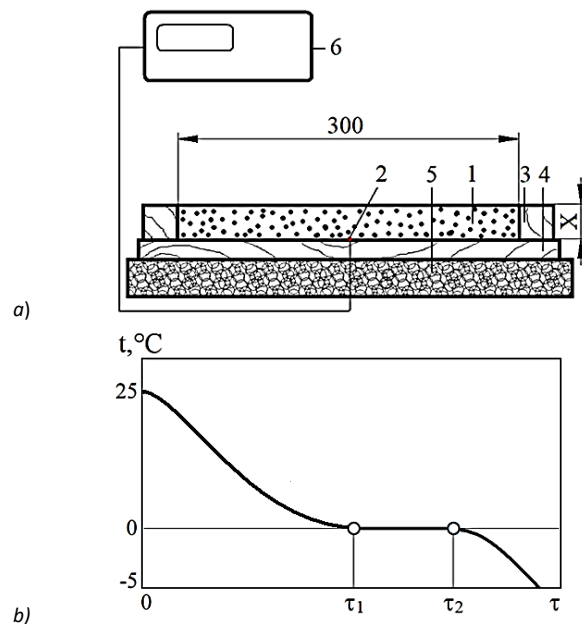


Figure 3. Scheme of the device (a) and typical dependence of the change in the temperature of wet sand over time during its freezing (b): 1 – compacted sand-water mixture; 2 – “hot” junction of the chromel-copel thermocouple; 3 – wooden frame; 4 – wooden plate 18 mm thick; 5 – foam plate 30 mm thick; 6 – electronic potentiometer; X – thickness of the wet sand layer (10, 20, 30 mm)

A typical dependence of the change in the temperature of wet sand over time during its freezing is presented in Fig. 3b, where τ_1 , τ_2 are the time of the beginning and end of the hardening of water in the sand-water mixture, respectively, which were recorded during the tests. To determine the change in the water content in the surface layer, 5 mm thick of wet quartz sand, during its exposure to air before freezing and in different layers of wet sand after freezing, a sleeve with a sliding extension and a prefabricated sleeve were used. The layout of the layers in the sleeve with a sliding extension and the layers ($n_1 \dots n_3$) of wet sand in the prefabricated sleeve are shown in Fig. 4.

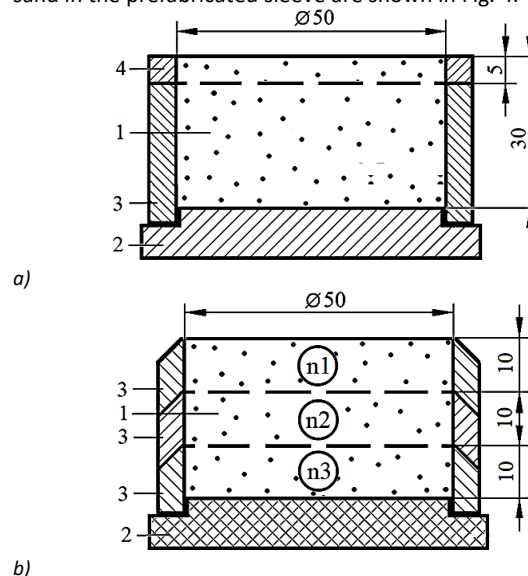


Figure 4. Scheme of arrangement of layers of wet sand in a sleeve with a sliding extension (a) scheme of arrangement of layers ($n_1 \dots n_3$) of wet sand in a collecting sleeve (b): 1 – wet sand; 2 – bottom; 3 – rings; 4 – sliding extension

According to the scheme in Fig. 4,a, wet sand was kept in air for a fixed time, after which it was cut off with an extension. The portion of sand remaining in the sliding extension was weighed,

dried in microwave radiation for 7 minutes and re-weighed. According to the results of weighing, the residual water content (B_{li}) in more than 100% quartz sand was calculated according to the formula (4), %.

$$B_{li} = 100 \cdot (M_{Bi} - M_p) / M_p, \quad (4)$$

where M_{Bi} is the initial mass of wet sand in the sliding attachment after the i -th time of its exposure in air, g; M_p is the mass of dry sand in the sliding attachment, g.

According to the scheme in Fig. 4,b, rings were removed from wet sand frozen for 12 hours in turn and layer by layer and the frozen sand was cut off. The portion of sand remaining in each ring was weighed, dried in microwave radiation for 7 minutes and re-weighed. Based on the results of weighing, the residual water content (B_l) in more than 100% quartz sand was calculated layer by layer using the formula (4). To determine the effect of the initial temperature of wet sand on the hardening time and cooling rate to 0 °C, the device according to the scheme in Fig. 5 was used.

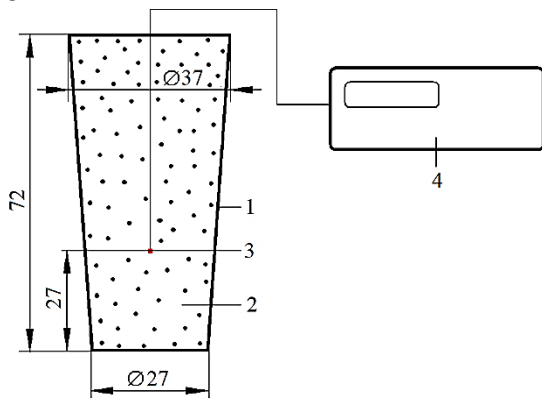


Figure 5. Schematic diagram of the thermocouple location in a conical sample of a sand-water mixture: 1 – polypropylene cup; 2 – sand-water mixture; 3 – hot junction of a chromel-copel thermocouple; 4 – electronic potentiometer

To determine the specified parameters, wet sand with a water content of 7.5% on top of 100% quartz sand was poured and compacted in a polypropylene container. After compaction, the container was cooled to -5 °C according to the readings of an electronic potentiometer from a thermocouple (see Fig. 5) with video recording of temperature changes over time with an interval of 1 s. In all experiments, time values were determined based on the results of video recording with an accuracy of 1 s.

4 RESULTS AND DISCUSSION

The dependence of temperature on the cooling time of quartz sand at -20 °C in layers of different thicknesses and with different water contents is presented in Fig. 6. From the analysis of the course of the dependencies in Fig. 6 it follows that flat product from sand-water mixtures with a thickness of 10 mm, regardless of the water content in them (up to 12.5% over 100% quartz sand), under conditions of unidirectional heat removal, cool to 0 °C faster than dry quartz sand. At the same time, the time of crystallization of water increases with an increase in its content in the sand, which is evidenced, in particular, by the data of tables 1 and 2, the dependencies in Fig. 7 and formulas (5) and (6).

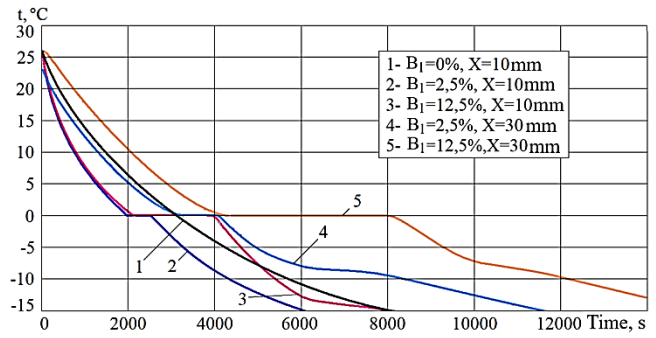


Figure 6. Temperature dependence of cooling time of dry sand at 20 °C in a layer 10 mm thick (1), wet sand with 2.5% water in a layer 10 mm thick (2), wet sand with 12.5% water in a layer 10 mm thick (3), wet sand with 2.5% water in a layer 30 mm thick (4), wet sand with 12.5% water in a layer 30 mm thick (5)

Table 1. Duration of cooling of quartz sand samples until the completion of water crystallization in them (τ_2)

X, mm	Duration of cooling (min) of quartz sand samples until the completion of crystallization of water in them with a mass water content			
	2.5 %	4.5 %	7.5 %	12.5 %
10	42	52	63	67
20	59	82	104	114
30	78	113	149	164

Table 2. Water crystallization time ($\tau_2 - \tau_1$) in quartz sand samples with a thickness (X) of 10 to 30 mm

X, mm	Duration of water crystallization in quartz sand samples (min) with a mass content of water in them			
	2.5 %	4.5 %	7.5 %	12.5 %
10	12.7	19.5	25.9	34.6
20	16.8	25.5	35.0	47.6
30	24.0	36.4	49.0	66.9

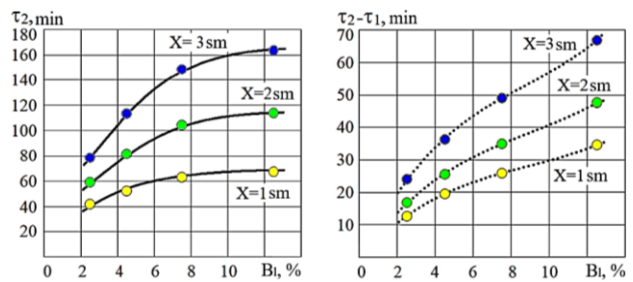


Figure 7. Dependence of the hardening time of the sand-water mixture (a) and the duration of water crystallization (b) in the sand-water mixture on the mass content of water in it (B_l) and the layer thickness (X)

Formula (5) for calculating the hardening time of a sand-water mixture (completion of water crystallization in the mixture layer), min:

$$\tau_2 = (400 \cdot X^{-1.2} + 7,5 \cdot B_l - 0,33 \cdot B_l^2) \cdot (0,1 \cdot X)^{1,1}, \quad (5)$$

where X is the thickness of the sand-water mixture layer, mm; B_l is the mass content of water in the sand-water mixture, %.

Formula (6) for calculating the time of crystallization of water in a sand-water mixture (duration of crystallization of water in the mixture at depth X), min:

$$\tau_{cr} = \tau_2 - \tau_1 = A \cdot (0,847 + 0,003956 \cdot X + 0,001104 \cdot X^2) \quad (6)$$

$$A = 0,0204 \cdot B_l^3 - 0,5494 \cdot B_l^2 + 6,4749 \cdot B_l - 0,3237$$

Using formula (5), a nomogram was constructed to determine the cooling time and completion of crystallization of water in it from its content in quartz sand and the thickness of its layer, which is presented in Fig. 8.

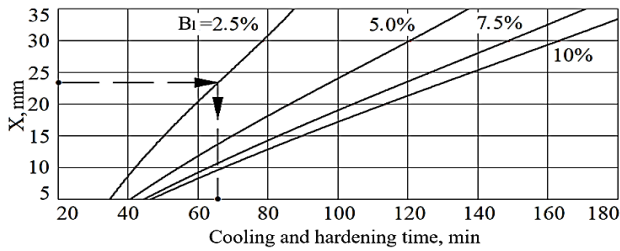


Figure 8. Nomogram for determining the cooling and hardening time of a sand-water mixture with a predominant sand grain size of 0.2 mm at a temperature of $-20\text{ }^{\circ}\text{C}$, depending on the thickness of its layer (X) and the water content in it ($B_i, \%$)

It should be noted that with an increased water content and/or thickness of the sand-water mixture layer at a temperature below $-7\text{ }^{\circ}\text{C}$, the cooling rate of the hardened mixture slows down (see dependencies 3...5 in Fig. 6). At the same time, the temperature at which the cooling rate of the studied mixtures begins to decrease is lower, the smaller the thickness of the cooled layer and the less water it contains.

The reason for this change in the cooling rate is probably the formation of an air gap between the cooled mixture and the wooden board on which it was formed. In turn, one of the reasons for this gap is due to the expansion of ice in the intergranular space of the mixture as it cools in the space limited by the perimeter of the mixture by a rigid wooden frame. That is, the compressive stresses along the perimeter of the frozen mixture led to its grooving. Another reason for the formation of grooving is the accumulation of water in the layers of the mixture below during its successive solidification in the mixture layer. In essence, the formation of this air gap (grooving) has the same nature as soil swelling - an increase in the volume of the soil when water freezes in its pores.

As noted above, one of the conditions for swelling is the retention of a significant amount of water by the soil. In this regard, soils with loam are most often prone to swelling. Under the conditions for swelling to occur, water must accumulate in the mixture layer adjacent to the wooden board. To identify the dependence of the change in water content in the surface layer of compacted quartz sand with 7.5% water on the time of its exposure in air at $25\text{ }^{\circ}\text{C}$ and layers of frozen sand-water mixtures with different initial water content B_{ib} , studies were conducted using the devices presented in Fig. 4. The results of the studies are presented in the form of dependences in Fig. 9.

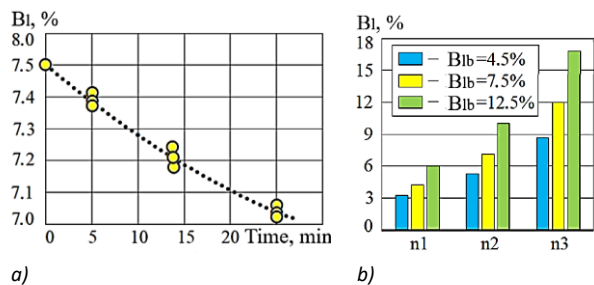


Figure 9. Dependence of water content in a 5 mm surface layer of compacted quartz sand with 7.5% water on its exposure time in air at $25\text{ }^{\circ}\text{C}$ (a) and layers n1...n3 (see Fig. 4b) of frozen sand-water mixtures with an initial water content B_{ib} (b)

From the analysis of the course of the dependences in Fig. 9a it follows that from the moment of completion of the compaction of wet sand, there is a slow movement of water under the action of gravity and capillary forces in the direction of gravity. In

addition, water also partially evaporates from the open surface of the mixture. As a result, the surface layer of wet sand is dehydrated. That is, the relative magnitude of such surface dehydration also depends on the temperature, speed of movement, and relative humidity of the air in which the wet sand is located. From the obtained result, it follows that in production conditions, it is desirable to place wet sand in a refrigerator for freezing no later than 5 minutes after its compaction in the equipment.

From the analysis of the course of the dependencies in Fig. 9,b it follows that the freezing of wet sand under conditions of multidirectional heat removal from it leads to the migration of water in the sand in the direction of gravity, i.e. from the front of solidification of wet sand to the surface with a higher temperature, which in terms of the direction of movement of unfrozen water contradicts the data of C. Dirksen, R. Miller (1966), E. Ershova et al. (1984) for soils that are semi-infinite bodies. A probable reason for the migration of water in a product of finite dimensions is the increased volume of ice compared to the volume of water from which it arose. This circumstance, obviously, in conditions of inhibition by the equipment of the natural expansion of the mixture during its solidification leads to the displacement of air and water from the capillary channels of the mixture into its warmer horizons of the product (sample). The effect of initial temperature on the rate and time of hardening of wet sand in the final size sample was investigated for mixtures of quartz sand with 7.5% water (over 100% quartz sand) and initial temperatures of $28\text{ }^{\circ}\text{C}$ and $60\text{ }^{\circ}\text{C}$, using the equipment, the scheme of which is given in Fig. 5. The temperature-time dependences of conical samples of mixtures of quartz sand with 7.5% water (over 100% quartz sand) and initial temperatures of $28\text{ }^{\circ}\text{C}$ and $60\text{ }^{\circ}\text{C}$ are given in Fig. 10.

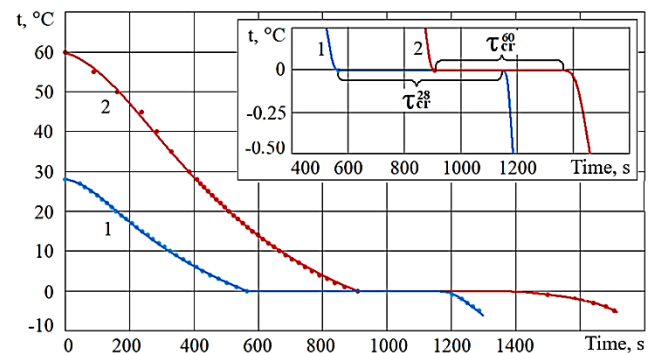


Figure 10. Temperature dependences over time of conical samples of quartz sand mixtures with 7.5% water (over 100% quartz sand) and initial temperatures of $28\text{ }^{\circ}\text{C}$ (1) and $60\text{ }^{\circ}\text{C}$ (2)

From the analysis of the dependences in Fig. 5 it follows that increasing the initial temperature of the sand-water mixture by more than two times (from $28\text{ }^{\circ}\text{C}$ to $60\text{ }^{\circ}\text{C}$) leads to an increase in the time of its cooling and hardening by only 15%. At the same time, the cooling rate of the sand-water mixture with an increased initial temperature is greater than the cooling rate of the mixture with a lower initial temperature. In particular, under the conditions of this experiment, the average cooling rate of the sand-water mixture from $60\text{ }^{\circ}\text{C}$ to $0\text{ }^{\circ}\text{C}$ was $4.2\text{ }^{\circ}\text{C}/\text{min}$, and the average cooling rate of the sand-water mixture from $28\text{ }^{\circ}\text{C}$ to $0\text{ }^{\circ}\text{C}$ was $3.1\text{ }^{\circ}\text{C}/\text{min}$. This pattern can be explained by a decrease in the level of surface tension of water with an increase in its temperature, which contributes to an increase in the size of the water cuffs between the grains of sand and, accordingly, an increase in the thermal conductivity coefficient of the sand-water mixture. At the same time, the duration of water crystallization ($\tau_{cr} = \tau_2 - \tau_1$) in a mixture with an increased initial temperature (see Fig. 5) is less than the duration of water crystallization in a mixture with a lower temperature. In

particular, the duration of water crystallization in a mixture with an initial temperature of 60 °C is 43..46 s less than the duration of water crystallization in a mixture with an initial temperature of 28 °C. This indicates that at the temperature measurement point the water content in the sand-water mixture with an initial temperature of 60 °C was lower than in the mixture with an initial temperature of 28 °C. It is likely that this pattern is due not to the migration of water to the front of its solidification in the mixture, but to the increased air humidity in the capillaries of a more heated (warm) mixture. An increase in the moisture in the air of the capillary channels of the sand-water mixture in the presence of a temperature gradient during its cooling leads to an increase in moisture condensation at the crystallization front and, accordingly, a decrease in the water content in the adjacent layers of the mixture with a higher temperature. That is, with an increase in the initial temperature of the sand-water mixture during freezing under conditions of multidirectional heat removal from it, the direction of water migration changes - from the internal parts to the water crystallization front, which coincides with the results of research by C. Dirksen, R. Miller (1966), E. Ershova et al. (1984) for soils as semi-infinite bodies.

5 CONCLUSIONS

According to the results of the research, the following features of freezing sand-water mixtures in products of final sizes in a refrigeration chamber were established.

Flat products with a thickness of 10 mm, regardless of the water content (up to 12.5% over 100% quartz sand), are cooled to 0 °C faster than dry quartz sand under conditions of unidirectional heat removal.

In wet sand under conditions of unidirectional heat removal, mass transfer mainly occurs due to the movement of water by the capillary-gravity mechanism from top to bottom, which leads to its accumulation in the lower horizon of the mixture and the formation of grooves in the frozen sand layer during its further cooling below -7 °C. Based on this, when manufacturing frozen products of final sizes from wet sand, it is advisable to limit the freezing process to the time at which the temperature at the warmest point of the product drops to -1 °C.

Since from the moment of completion of compaction of wet sand, water slowly moves under the action of gravity and capillary forces in the direction of gravity, in production conditions, it is advisable to place wet sand in a refrigeration chamber for freezing no later than 5 minutes after its compaction in the equipment.

Freezing of wet sand in conditions of multidirectional heat removal from it leads to a significant migration of water in the sand in the direction of gravity, i.e. from the front of solidification of wet sand to a surface with a higher temperature, which is in the direction of movement of unfrozen water.

Increasing the initial temperature of wet sand contributes to an increase in the rate of its cooling to 0 °C and the time of solidification of water, but increases the total time of solidification of wet sand.

ACKNOWLEDGMENTS

The authors would like to thank the KEGA grant agency for supporting research work and co-financing the project KEGA 008TUKE-4/2025.

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